Chapter I.   INTRODUCTION

Precision measurements of the properties of the neutron present an opportunity to search for violations of fundamental symmetries and to make critical tests of the validity of the Standard Model (SM) of Electro-Weak (EW) Interactions. These have been pursued with great energy and interest since Chadwick [1] discovered the neutron in 1932. The currently accepted values for the properties of the neutron, and related particles, from the Particle Data group [2] are listed in Tables I.A and I-B. In the past few years, the development of more intense sources of cold and ultracold neutrons and the invention of new trapping and detection techniques have sparked a new attack on these fundamental measurements. Examples of these are the new measurement of the neutron lifetime being developed with a ^{4}He based ultra-cold neutron (UCN) trap at the NIST reactor [3] and the new proposed measurement of the neutron beta decay asymmetry parameter, *A*, using a solid deuterium based UCN moderator at LANSCE [4].

In this proposal we discuss a new technique for searching for the electric dipole moment (EDM) of the neutron which offers unprecedented sensitivity. It is based on the traditional magnetic resonance technique in which a neutron's magnetic dipole moment is placed in a plane perpendicular to parallel magnetic and electric fields, B_0 and E_0. It will precess with a Larmor frequency, ν_n (Hz),

$$h\nu_n = -\left[2\mu_n B_0 + 2d_n E_0\right] , \tag{I.1}$$

Here μ_n (d_n) is the magnetic (electric) dipole moment of the neutron, (see Table I-B), where μ_{nuclear} is the nuclear magneton.

Table I-A. Experimental limits on the EDM of fundamental particles, [2].

Particle	**Experimental EDM Value / Limit ($e{\cdot}$cm)**
Electron, e	$0.18 \pm 0.16 \pm 0.10 \times 10^{-26}$
Neutron, n	$< 0.63 \times 10^{-25}$ [90% C.L.]
Proton, p	$-3.7 \pm 6.3 \times 10^{-23}$
Lambda Hyperon, Λ	$< 1.5 \times 10^{-16}$ [95% C.L.]
Tau Neutrino, ν_τ	$< 5.2 \times 10^{-17}$ [95% C.L.]
Muon, μ	$3.7 \pm 3.4 \times 10^{-19}$
Tau, τ	$< 3.1 \times 10^{-16}$ [95% C.L.]

The impact of the *E* field on the precession of the neutron is characterized by the first moment of the neutron charge distribution, d_n, its EDM. All experiments to date have assigned a zero value to the neutron EDM.

Table I-B. Fundamental properties of the neutron, atomic ^{3}He, and superfluid ^{4}He, [2].

The Neutron	
Intrinsic Spin, S	$1/2\hbar$
Mass, m_n	939.565330 ± 0.000038 MeV 1.00866491578 a.m.u.
Mean Life, τ_n	886.7 ± 1.9 s
Magnetic Moment, μ_n	-1.91304272 ± 0.00000045 μ_{nuclear}
Electric Dipole Moment, d_n	$< 0.63 \times 10^{-25}$ [90% C.L.]
Electric Polarizability, α_n	$0.98 \pm 0.21 \times 10^{-3}$ fm^3
Charge, q	$-0.4 \pm 1.1 \times 10^{-21}$ e
Atomic ^{3}He	
Intrinsic Nuclear Spin, S	$1/2\hbar$
Mass, $m_{^3\mathrm{He}}$	3.016030 a.m.u.
Mean Life, $\tau_{^3\mathrm{He}}$	stable
Magnetic Dipole Moment, $\mu_{^3\mathrm{He}}$	–2.12762486 μ_{nuclear}
$\mu_{^3\mathrm{He}}/\mu_n$	1.11217
Electric Dipole Moment, $d_{^3\mathrm{He}}$	~ 0
Superfluid ^{4}He	
Density at 3.5°K	0.14 gm/cm^3
Dielectric Constant, ε	1.05 ε_o

Searches for the EDM of the neutron date back to a 1957 paper of Purcell and Ramsey [5]. This led to an experiment using a magnetic resonance technique at ORNL, where they established a value of $d_n = -0.1 \pm 2.4 \times 10^{-20}$ e·cm [6]. Using Bragg scattering, an MIT/BNL experiment used neutron scattering from a CdS crystal to search for the neutron EDM [7], and obtained a value of $d_n = 2.4 \pm 3.9 \times 10^{-22}$ e·cm. In the intervening 30 years, a series of measurements of increasing precision have culminated in the current best limit of $d_n < 0.63 \times 10^{-25}$ e·cm [90% C.L.] obtained in measurements at the ILL reactor at Grenoble [8]. Thus there has been an impressive reduction with time of the experimental limit for d_n as illustrated in Fig I-1 and reviewed in Chapter III.

We describe here a new technique [9] that promises a two order of magnitude improvement over the ILL result [8]. An overview of this new technique is presented in Section IV of this proposal. A detailed and quantitative analysis of the method is presented in Section V.

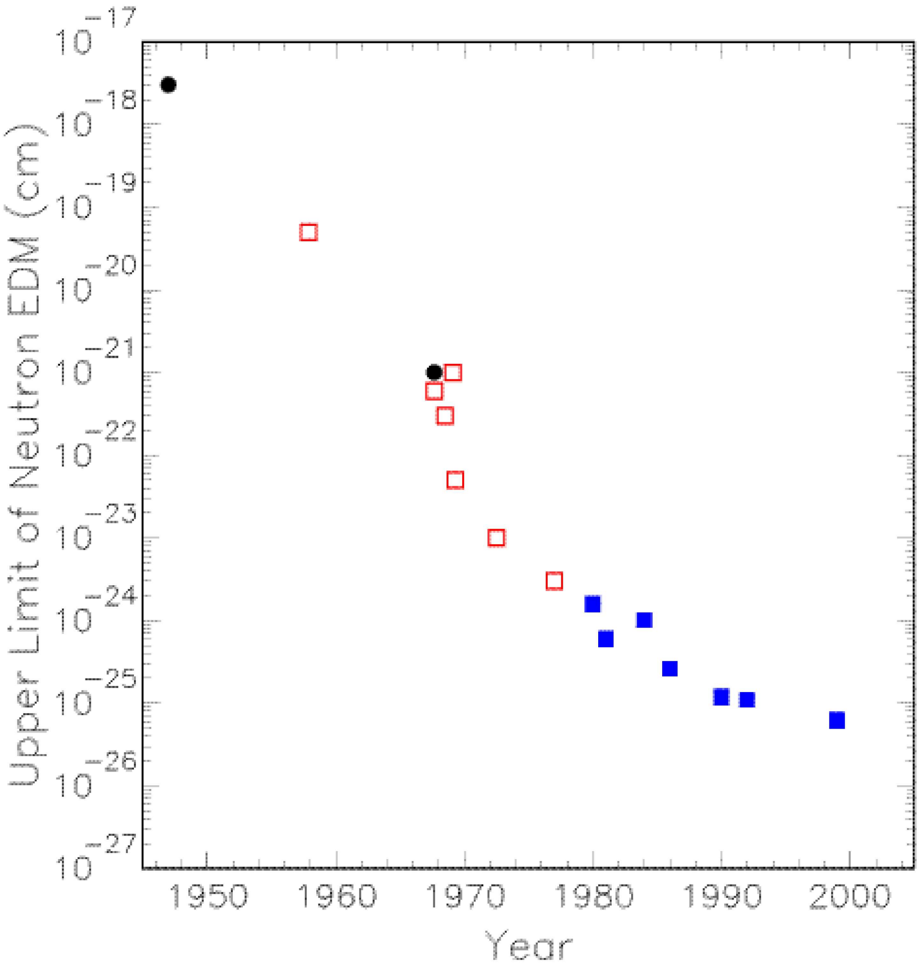

Fig. I-1. Upper limits of neutron EDM plotted as a function of year of publication. The solid circles correspond to neutron scattering experiments. The open squares represent in-flight magnetic resonance measurements, and the solid squares signify UCN magnetic resonance experiments.

The physics motivation for these measurements has been widely discussed. A search for a non-zero value of the neutron EDM is a search for a violation of T invariance. To date there is only one measurement (a comparison of neutral K and $\overline{K}$ meson decay) in which T violation has been seen directly [10]. The asymmetry in these rates is found to be $6.6 \pm 1.3 \pm 1.0 \times 10^{-3}$. In the EW sector, one has a strong prejudice that the combined symmetry operation, CPT, is invariant in all processes. However, examples have been known for several decades where both P and C invariance are separately violated. Thus observation of a violation of T invariance through measurement of the neutron EDM would be of fundamental significance.

The SM prediction for the neutron EDM, as characterized by the CKM matrix, is at the 10^{-31} $e\cdot$cm level, below the reach of current measurements by six orders of magnitude [11]. Although no violation of the SM has been observed (except perhaps for recent measurements of the neutrino mass), there are many proposed models of the EW interaction which are extensions beyond the SM and which raise the predicted value of the neutron EDM by up to seven orders of magnitude (see Chapter II). Some of these are already excluded by the current limit on the neutron EDM. The proposed experiment has the potential to reduce the acceptable range for predictions by two orders of magnitude and to provide a significant challenge to these extensions to the SM. Conversely, if a new source of CP violation is present in nature, beyond the CKM matrix description in the SM, and which is relevant to this hadron system, this experiment offers an intriguing opportunity to measure a non-zero value of the neutron EDM.

Our understanding of the origins of baryogenesis provides one reason for thinking that other sources of CP violation might exist beyond that found in the K-Kbar and B-Bbar systems. In the Big Bang one expects the generation of equal populations of particles and anti-particles. Current experimental observations yield the predominately particle universe and we have no mechanism that would push the anti-particle universe away to a different region of space. Thus it is tempting to assume that in some unknown reaction process, occurring early in the life of the universe and involving CP violation, the anti-particles were largely consumed. The required character of this unknown process has been analyzed by Sakharov [12] as discussed in Chapter II. Recent calculations suggest that the strength of the CP-violating mechanism required to produce the observed baryon asymmetry, would have to be much stronger than that required to explain the ε' measurements in the $K\overline{K}$ system [13]. This observation provides a hint that the SM calculation may not be complete and invites investigation of extensions to the SM. Thus predictions that the EDM of the neutron may be larger than the predictions in the SM need to be taken seriously.

The current experimental limits on the EDM of other fundamental particles, are compared with the neutron in Table I-A. We believe the EDM of the neutron and the electron provide the most sensitive tests of the SM. In theories of the weak interaction, the EDM of the electron is zero in first order. There have been a number of precision measurements of the EDM of paramagnetic atomic systems, from which limits for the EDM of the electron can be inferred. For example, the measurements in Tl by Commins et al [14] suggest a value of $0.18 \pm 0.12 \pm 0.10 \times 10^{-26}$ $e\cdot$cm. This experimental limit is about 13 orders of magnitude above the SM predictions. The electron EDM is discussed further in Chapter II.

Thus a neutron EDM measurement, with two orders of magnitude improvement over the current experimental limits, presents an excellent opportunity to challenge the extensions beyond the SM and to search for new physics in the CP sector. It also provides an opportunity to search for T violation in non-strange systems. A review of the physics implications of neutron EDM measurements is presented in Section II followed by a discussion of previous EDM measurements in Section III. After a description of the proposed technique in Sections IV and V, we discuss the collaboration, schedule, and costs associated with this project in Chapters VI and VII. Some outstanding technical issues are discussed in Appendix A.

References

[1] J. Chadwick, *Nature* **129**, 312 (1932); *Proc. Roy. Soc.* (London) **A136**, 692 (1932).
[2] D. E. Groom et al. (Particle Data Group), *Eur. Phys. J.* **C15**, 1 (2000).
[3] P. R. Huffman et al., *Nature* **403**, 62 (2000).
[4] R. E. Hill et al., *Nucl. Instrum. Methods* **440**, 674 (2000).
[5] E. M. Purcell and N. F. Ramsey, *Phys. Rev*. **78**, 807 (1950).
[6] J. H. Smith, E. M. Purcell, and N. F. Ramsey, *Phys. Rev*. **108**, 120 (1957).
[7] C. G. Shull and R. Nathans, *Phys. Rev. Lett*. **19**, 384 (1967).
[8] P. G. Harris et al., *Phys. Rev. Lett*. **82**, 904 (1999).
[9] G. Golub and S. K. Lamoreaux, *Phys. Rep*. **237**, 1 (1994), I. B. Khriplovich and S. K. Lamoreaux, *CP Violation without Strangeness* (Springer Verlag, 1997).
[10] A. Angelopoulos et al. (CPLEAR Collaboration), *Phys. Lett*. **444B**, 43 (1998).
[11] G. Buchalla et al., *Nucl. Phys*. **B370**, 69 (1992); A. J. Buras et al., *Nucl. Phys*. **B408**, 209 (1993); M. Ciuchini, *Nucl. Phys. Proc. Suppl*. **59**, 149 (1997).
[12] A. D. Sakharov, *JETP Lett*. **5**, 24 (1967).
[13] I. I. Bibi and A. I. Sanda, *CP Violation* (Cambridge University Press, 2000), p. 355.
[14] E. D. Commins, S. B. Ross, D. DeMille, and B. C. Regan, *Phys. Rev*. **A50**, 2960 (1994).